Calculation of flow rate from differential pressure devices – orifice plates

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- How is flow and pressure linked?
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- Differences between different version (1991 to 2003).
- Which other information's are essential in a given application?
- What influences the flow measurement result and how important is it?
- What uncertainties must we expect?

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Introduction 1 – Flow is always measured indirectly

- **Flow rate** – one of the most complex and difficult quantity to measure and to calibrate.
- **No principle** for direct measurement exists.
- **Many different physical measurement principles** – all have advantages and drawbacks.
- **Roundabout way** via speed, rotation speed, frequency, phase difference, temperature difference, force, voltage etc. (thousands of patents exist!)
- **But:** All metering devices need a calibration in one form or another.
- **Question:** How should we calibrate meters for use in hot water (> 300 °C, 180 bar) or steam?

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Introduction 2 – Standards for dp-meters

- **"Primary devices"** - measure pressure difference Δp produced by flow passing an obstruction and "calculate" the mass flow.
- **Any obstruction** can be used if the relation between **q** and **Δp** is well known.
- Orifice plates – Nozzles – Venturi tubes are standardized obstructions. But others exist as well.
- The standards tell detailed how to use these devices and what the limitations are.
- ISO 5167 Part 1, 2, 3 and 4 from 2003 (revision from 1991)
- ISO/TR 15377 contains complementing information to ISO 5167
- ASME MFC-3M, 2004 (revision from 1989)
- ASME PTC 6-2004 Performance Test Codes (revision from 1996)

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Introduction 3 – The Situation for Power Plants

- In the late 60-ties and 70-ties no robust flow measurement technique was available for the high temperature/pressure applications.
- The nuclear power industry is conservative and focused on safety.
- The thermal effect is limited to a licensed value.
- A flow measurement accuracy of 2 % kept the output at 98 % of rated effect.
- dp-devices showed no stable behavior due to fouling.
- Over the years a lot of measuring technique has been exchanged.

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Introduction 4 – Thermal Power Increase

- **"MUR"** – Measurement Uncertainty Recapture – is a trial to lower measurement uncertainty (mainly in flow), which in turn can be used to increase the thermal output closer to the rated effect.
- How can measurement uncertainty be reduced?
  - By calibration!
  - And by sensing of eventual changes over time!
- Who can calibrate flow meters at 330 °C, 180 bar, Re >10^7 ?
  - Nobody!
- What to use for sensing?
  - A second measurement principle!

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Introduction 5 - Difficulties in Meter Calibration

Gravimetric Method - (short traceability to kg, s, °C)

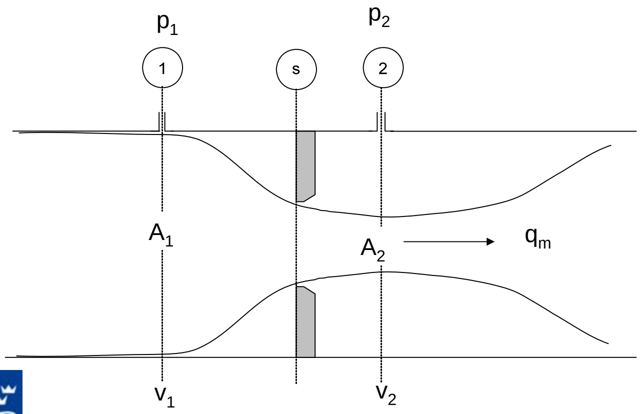
- The water must be kept at constant pressure and temperature
- Large amount of water – big vessels are needed
- Diverter and weighing tank in closed system to avoid steam evaporation

Volumetric Method - (longer traceability to m^3, ρ_{water}, s, °C)

- Pipe- or Ball prover (long big pipes – working under high pressure
- Suitable material for ball or piston to tighten at high temperature/pressure (lubrication)
- Large positive displacement meter as master meter

Flow is forced through the orifice

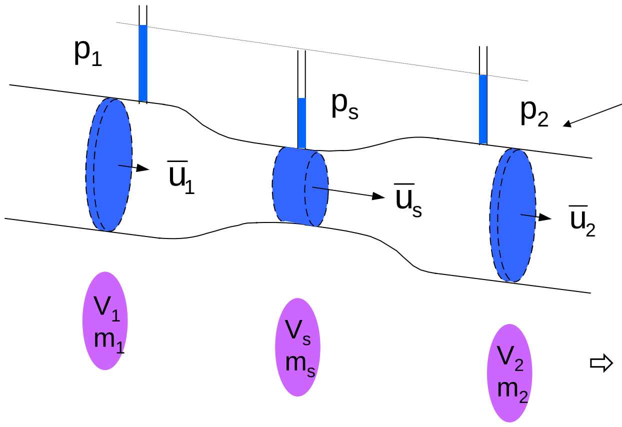
We need a standard to clear up how pressure p, speed v, flow q_m and flow area are interrelated and used to calculated mass flow from the pressure difference between point 1 and 2 with satisfactory measurement uncertainty?



Flow in pipe with change in cross area

Assume continuity and incompressibility

$$q_{m1} = A_1 \cdot \bar{u}_1 \cdot \rho$$
$$q_{m2} = A_2 \cdot \bar{u}_2 \cdot \rho$$



static pressure

Due to friction within the medium and with the wall pressure falls along the pipe.

⇨ $\bar{u}_s > \bar{u}_1$

$p_s < p_1$

Mass m_1 and volume V_1 of a ”flow element” does not change if area changes

Average speed increases, static pressure falls where the area is smaller.

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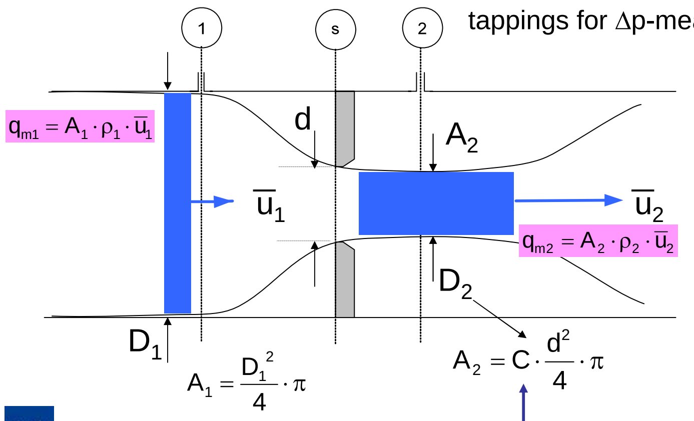
Measurement principle

Incompressibility means density does not change $\rho_2 = \rho_1$
Continuity means the flow is the same every where in the pipe $q_{m1} = q_{m2}$



D: pipe diameter
d: orifice diameter

Area at the smallest flow cross section not exactly known!

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Bernoullis equation on energy conservation

$$p_1 + \frac{1}{2}\rho_1\bar{u}_1^{\,2} = p_2 + \frac{1}{2}\rho_2\bar{u}_2^{\,2} = \text{const} = p_0$$

p_0: total pressure in medium
$p = p_0$ where $u = 0$

The sum of static and dynamic pressure is the same everywhere in pipe.

$$\Downarrow$$

$$\Delta p = p_1 - p_2 = \frac{\rho}{2}\left(\bar{u}_2^2 - \bar{u}_1^2\right)$$

$\frac{1}{2}\rho\bar{u}^2$: ”dynamic pressure”

Replace the speed terms through geometric measures and insert.

$$q_m = A\cdot\rho\cdot\bar{u}$$

$$\bar{u}_1^{\,2} = \frac{4^2\cdot q_m^{\,2}}{D_1^{\,4}\cdot\pi^2\cdot\rho^2}$$

$$\bar{u}_2^{\,2} = \frac{4^2\cdot q_m^{\,2}}{D_2^{\,4}\cdot\pi^2\cdot\rho^2}$$

$$\Delta p = \frac{\rho}{2}\cdot\frac{4^2 q_m^{\,2}}{\pi^2\cdot\rho^2}\left(\frac{1}{D_2^{\,4}} - \frac{1}{D_1^{\,4}}\right) \qquad \Delta p\cdot D_2^{\,4} = \frac{\rho}{2}\cdot\frac{4^2 q_m^{\,2}}{\pi^2\cdot\rho^2}\left(\frac{D_2^{\,4}}{D_2^{\,4}} - \frac{D_2^{\,4}}{D_1^{\,4}}\right)$$

$$2\cdot\Delta p\cdot\rho\cdot\pi^2\cdot D_2^{\,4} = 4^2 q_m^{\,2}\left(1 - \frac{D_2^{\,4}}{D_1^{\,4}}\right)$$

“Replace” D_2 with d, introduce β, solve for q_m

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Final equation for calculating q_m

$$q_m^{\,2} = \frac{1}{\left(1 - \frac{D_2^{\,4}}{D_1^{\,4}}\right)}\frac{\pi^2}{4^2}\cdot D_2^{\,4}\cdot 2\cdot\Delta p\cdot\rho$$

Exchange unknown D_2 with known d

$$\beta = \frac{d}{D}$$

Introduce a **discharge coefficient C** relating the unknown diameter D_2 to the known orifice diameter d!

Introduce an **expansion coefficient ε** for compressible media (gas, steam).

$$q_m = \frac{C}{\sqrt{1-\beta^4}}\cdot\varepsilon\cdot\frac{\pi}{4}\cdot d^2\cdot\sqrt{2\Delta p\cdot\rho_1}$$

To ”measure flow” means to determine Δp and use it in the equation with all other ”constants” and calculate q_m.

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Why a discharge coefficient?

C determines the relation between the real flow through a “primary device” and the theoretical possible flow.

For a given ”primary device” this dimensionless parameter is determined using an incompressible fluid. With fixed geometry C only depends on the actual Reynolds number. In a way C can be regarded as a ”calibration constant” for a ”primary device”.

Generally, different installations, that are geometrically equivalent and sense the same flow conditions and are characterized by the same Reynolds number, renders the same value for C.

But: Re varies with pressure, temperature, viscosity and flow. And so does C.

It is not easy to analyse the effect of different parameters on the flow.

Why an expansibility factor

ε expresses the different compressibility of different fluids (gases, steam), i.e. molecules are, depending on their form more or less compressed when passing the orifice. $\varepsilon \leq 1$

Water and other liquids are considered incompressible

⇨ $\varepsilon = 1$.

This makes calculations much simpler.

The size of ε depends on the pressure relation and the isentropic coefficient κ, i.e. the relation between a relative change in pressure and the corresponding relative change in density. κ is a property that is different for different media and varies also with the pressure and temperature of the medium.

For many gases there are no published data for κ. The standard recomends to use c_P/c_V.

What does the standards treatise on?

- Allowed variations for different measures (pipe diameter, orifice diameter, distance to upstream disturbances).
- Tolerances for all measures.
- How orifices must be installed.
- How thick the orifice can be and how much it may buckle.
- Which tolerances in angle are allowed
- How sharp or round the edges have to be.
- Which upstrem surface roughness the pipe must underpass.
- How the pressure tappings may be shaped and where they must be placed.
- How the tappings must be arranged in detail (diameter of drilled hole, smoothness of pipe wall, distance to possible flow disturbances etc.)

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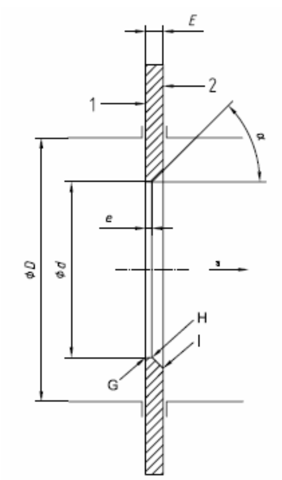
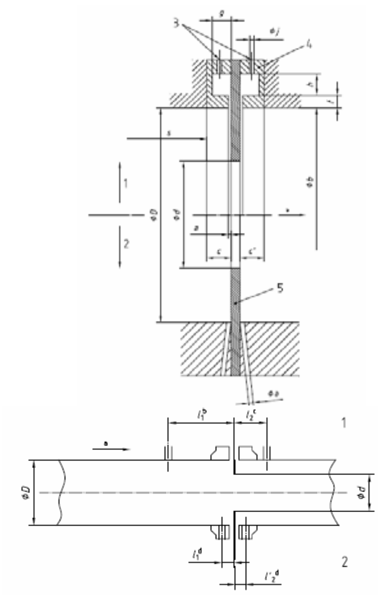
Orifice plates (part 2 of ISO 5167)





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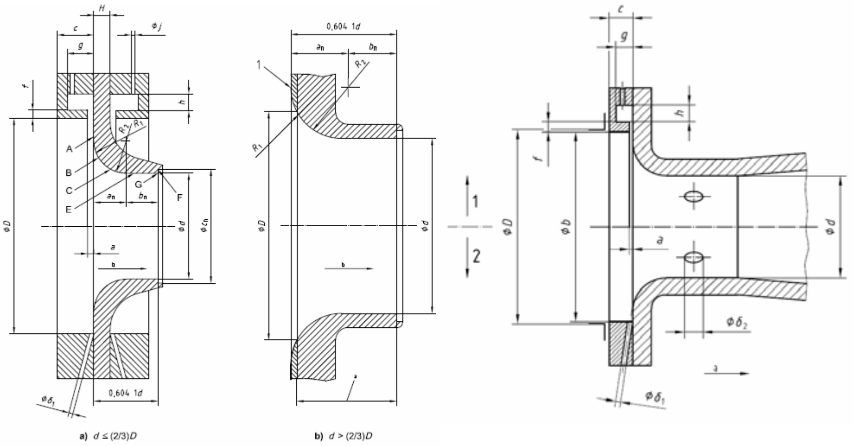
Isa - och Venturi nozzles (part 3 of ISO 5167)

D: 50 – 500 mm
β: 0,3 – 0,8
Re_D: $7{\times}10^4 – 2{\times}10^7$ för $\beta <$ 0,44
Re_D: $2{\times}10^4 – 2{\times}10^7$ för $\beta >$ 0,44

D: 65 – 500 mm
β: 0,316 – 0,775
Re_D: $1{,}5{\times}10^5 – 2{\times}10^6$

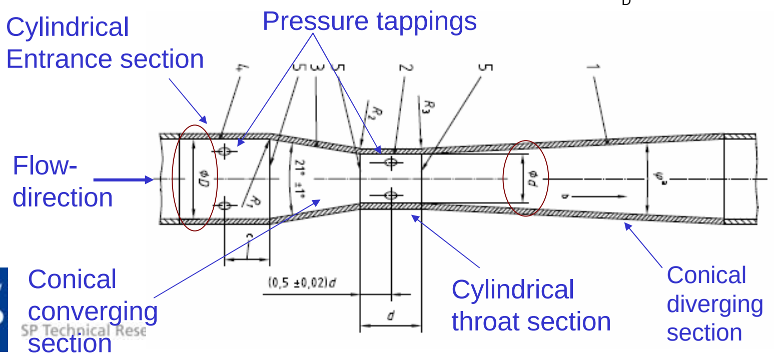


Venturi tubes (part 4 of ISO 5167)

All specified measures have to follow certain tolerances (not at least the surface roughness) and must be verified by measurement at several places.

Production by
a) cast
b) machined
c) welded

a) D: 100 – 800 mm
β: 0,3 – 0,75 Re_D: $2{\times}10^5 – 2{\times}10^6$
b) D: 50 – 250 mm
β: 0,4 – 0,75 Re_D: $2{\times}10^5 – 1{\times}10^6$
c) D: 200 – 1200 mm
β: 0,4 – 0,7 Re_D: $2{\times}10^5 – 2{\times}10^6$



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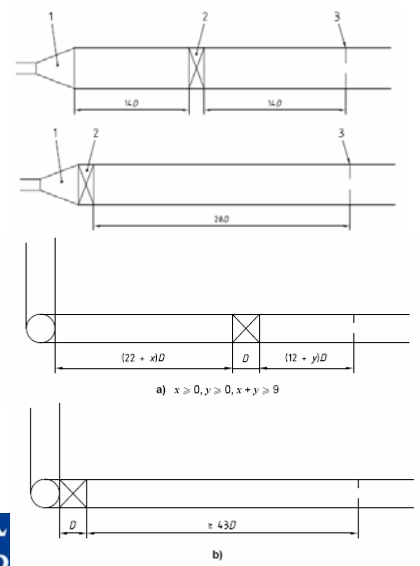
The standard gives advice by installation examples



1: conical diameter increase
2: totally open valve
3: place for orifice
4: 90° elbow

As long as certain distances (in multiples of D) between the orifice (or other dp-devices) and upstream disturbances are kept, the uncertainties stated in the standard are valid.

No extra uncertainties need to be added.

A table for lowest distance to different installation disturbances are given in a table.

Table for critical distances to upstream disturbances

Table 3 — Required straight lengths between orifice plates and fittings without flow conditioners

Values expressed as multiples of internal diameter, D

Diameter ratio β	Upstream (inlet) side of orifice plate																										Downstream (outlet) side of the orifice plate	
	Single 90° bend Two 90° bends in any plane ($S > 30D$)[a]		Two 90° bends in the same plane: S-configuration ($30D \geqslant S > 10D$)[a]		Two 90° bends in the same plane: S-configuration ($10D \geqslant S$)[a]		Two 90° bends in perpendicular planes ($30D \geqslant S \geqslant 5D$)[a]		Two 90° bends in perpendicular planes ($5D > S$)[a, b]		Single 90° tee with or without an extension Mitre 90° bend		Single 45° bend Two 45° bends in the same plane: S-configuration ($S \geqslant 2D$)[a]		Concentric reducer $2D$ to D over a length of $1{,}5D$ to $3D$		Concentric expander $0{,}5D$ to D over a length of D to $2D$		Full bore ball valve or gate valve fully open		Abrupt symmetrical reduction		Thermometer pocket or well[c] of diameter $\leqslant 0{,}03D$[d]		Fittings (columns 2 to 11) and the densitometer pocket	
1	2		3		4		5		6		7		8		9		10		11		12		13		14	
—	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]
⩽ 0,20	6	3	10	[g]	10	[g]	19	18	34	17	3	[g]	7	[g]	5	[g]	6	[g]	12	6	30	15	5	3	4	2
0,40	16	3	10	[g]	10	[g]	44	18	50	25	9	3	30	9	5	[g]	12	8	12	6	30	15	5	3	6	3
0,50	22	9	18	10	22	10	44	18	75	34	19	9	30	18	8	5	20	9	12	6	30	15	5	3	6	3
0,60	42	13	30	18	42	18	44	18	65[h]	25	29	18	30	18	9	5	26	11	14	7	30	15	5	3	7	3,5
0,67	44	20	44	18	44	20	44	20	60	18	36	18	44	18	12	6	28	14	18	9	30	15	5	3	7	3,5
0,75	44	20	44	18	44	22	44	20	75	18	44	18	44	18	13	8	36	18	24	12	30	15	5	3	8	4

NOTE 1 The minimum straight lengths required are the lengths between various fittings located upstream or downstream of the orifice plate and the orifice plate itself. Straight lengths shall be measured from the downstream end of the curved portion of the nearest (or only) bend or of the tee or the downstream end of the curved or conical portion of the reducer or the expander.

NOTE 2 Most of the bends on which the lengths in this table are based had a radius of curvature equal to $1{,}5D$.

[a] S is the separation between the two bends measured from the downstream end of the curved portion of the upstream bend to the upstream end of the curved portion of the downstream bend.

[b] This is not a good upstream installation; a flow conditioner should be used where possible.

[c] The installation of thermometer pockets or wells will not alter the required minimum upstream straight lengths for the other fittings.

[d] A thermometer pocket or well of diameter between $0{,}03D$ and $0{,}13D$ may be installed provided that the values in Columns A and B are increased to 20 and 10 respectively. Such an installation is not, however, recommended.

[e] Column A for each fitting gives lengths corresponding to "zero additional uncertainty" values (see 6.2.3).

[f] Column B for each fitting gives lengths corresponding to "0,5 % additional uncertainty" values (see 6.2.4).

[g] The straight length in Column A gives zero additional uncertainty; data are not available for shorter straight lengths which could be used to give the required straight lengths for Column B.

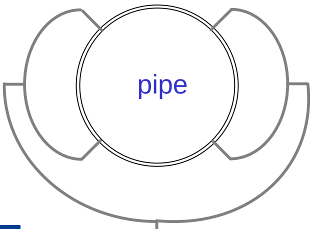
[h] $95D$ is required for $Re_D > 2 \times 10^6$ if $S < 2D$.

Measurement of pressure and differential pressure

- In flow computers or intelligent transmitters the density for the known liquid or gas is calculated from equations of state if pressure, temperature and gas composition is known.

- The measurement of static pressure p and differential pressure Δp should be separated. A correct Δp is of outmost importance.

Pressure i triple –T form



Pressure transmitter for Δp

To be observed in Δp-measurement

- Zero point adjustment
- Clogged pressure tappings/lines
- Pressure lines must be easily drained or ventilated
- No disturbances for flow close to the pressure tappings

Discharge coefficient C for orifice plates

Purpose: defines the relation of jet flow diameter to orifice diameter and distance to pressure tappings.

$$C = 0{,}5961 + 0{,}0261 \cdot \beta^2 - 0{,}216 \cdot \beta^8 + 0{,}000521 \cdot \left(\frac{10^6 \cdot \beta}{Re_D}\right)^{0,7} + (0{,}0188 + 0{,}0063 \cdot A) \cdot \beta^{3,5} \cdot \left(\frac{10^6}{Re_D}\right)^{0,3}$$

$$+ \left(0{,}043 + 0{,}080 \cdot e^{-10L1} - 0{,}123 \cdot e^{-7L1}\right) \cdot (1 - 0{,}11 \cdot A) \cdot \frac{\beta^4}{1-\beta^4}$$

$$- 0{,}031 \cdot \left(M_2 - 0{,}8 \cdot M_2^{1,1}\right) \cdot \beta^{1,3}$$

Data on pipe orifice plate medium

Data on upstream pressure tappings

Data on downstream pressure tappings

$\beta = \frac{d}{D}$ relation between orifice and pipe diameter

A function of β and Re_D $\quad A = \left(\frac{19000 \cdot \beta}{Re_D}\right)^{0,8}$

M_2 function of β and L_2 $\quad M_2 = \frac{2 \cdot L2}{1-\beta}$

Reader-Harris Gallagher Equation

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Standards are updated from time to time

ISO 5167 (1991) & ASME MFC-3M (2004) | **ISO 5167 (1991)**

Discharge coefficient

$$C = 0{,}5961 + 0{,}0261 \cdot \beta^2 - 0{,}216 \cdot \beta^8 + 0{,}000521 \cdot \left(\frac{10^6 \cdot \beta}{Re_D}\right)^{0{,}7} + (0{,}0188 + 0{,}0063 \cdot A) \cdot \beta^{3{,}5} \cdot \left(\frac{10^6}{Re_D}\right)^{0{,}3} + (0{,}043 + 0{,}080 \cdot e^{-10L1} - 0{,}123 \cdot e^{-7L1}) \cdot (1 - 0{,}11 \cdot A) \cdot \frac{\beta^4}{1-\beta^4} - 0{,}031 \cdot (M_2 - 0{,}8 \cdot M_2^{1{,}1}) \cdot \beta^{1{,}3}$$

Reader-Harris Gallagher equation

$$C = 0{,}5959 + 0{,}0312 \cdot \beta^{2{,}1} - 0{,}1840 \cdot \beta^8 + 0{,}0029 \cdot \beta^{2{,}5} \cdot \left(\frac{10^6}{Re_D}\right)^{0{,}75} + 0{,}0900 \, L_1 \cdot \beta^4 \cdot (1-\beta^4)^{-1} - 0{,}0337 \cdot L_2' \cdot \beta^3$$

Stolz equation

Expansibility factor

$$\varepsilon = 1 - (0{,}351 + 0{,}256 \cdot \beta^4 + 0{,}93 \cdot \beta^8) * \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{1}{\kappa}}\right]$$

$$\varepsilon = 1 - (0{,}41 + 0{,}35 \cdot \beta^4) \cdot \frac{\Delta p}{\kappa \cdot p_1}$$

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Different flow result with new version from 2003

Difference in air flow calculation using different versions of ISO 5167

ISO 5167	Flow rate 1991	Flow rate 2003	Flow rate Diff [%]	Expansion coefficient 1991	Expansion coefficient 2003	Expansion coefficient Diff [%]	Discharge Coefficient 1991	Discharge Coefficient 2003	Discharge Coefficient Diff [%]
	887,69	893,51	**0,651**	0,9908	0,9909	**0,008**	0,60027	0,60416	**0,643**
Air 0 ºC	1261,25	1268,26	**0,553**	0,9827	0,9828	**0,010**	0,59940	0,60267	**0,543**
	1783,36	1791,27	**0,442**	0,9673	0,9673	**-0,002**	0,59872	0,60139	**0,443**
	2207,29	2215,05	**0,350**	0,9527	0,9524	**-0,034**	0,59838	0,60069	**0,384**
	864,00	869,87	**0,676**	0,9909	0,991	**0,008**	0,60053	0,60457	**0,667**
Air 20 ºC	1210,12	1217,17	**0,580**	0,9827	0,9828	**0,010**	0,599616	0,60305	**0,570**
	1710,95	1719,00	**0,468**	0,9673	0,9672	**-0,002**	0,598888	0,60172	**0,470**
	2117,62	2125,62	**0,377**	0,9527	0,9524	**-0,034**	0,598526	0,60099	**0,410**
	821,20	827,09	**0,713**	0,9909	0,991	**0,008**	0,600942	0,60521	**0,704**
Air 50 ºC	1150,09	1157,23	**0,617**	0,9827	0,9828	**0,010**	0,599936	0,6036	**0,607**
	1626,11	1634,37	**0,505**	0,9672	0,9672	**-0,002**	0,599135	0,60219	**0,507**
	2012,77	2021,11	**0,413**	0,9527	0,9523	**-0,034**	0,598736	0,60142	**0,446**

The difference is predominantly caused by the discharge coefficient. The change in C decreases with increasing flow

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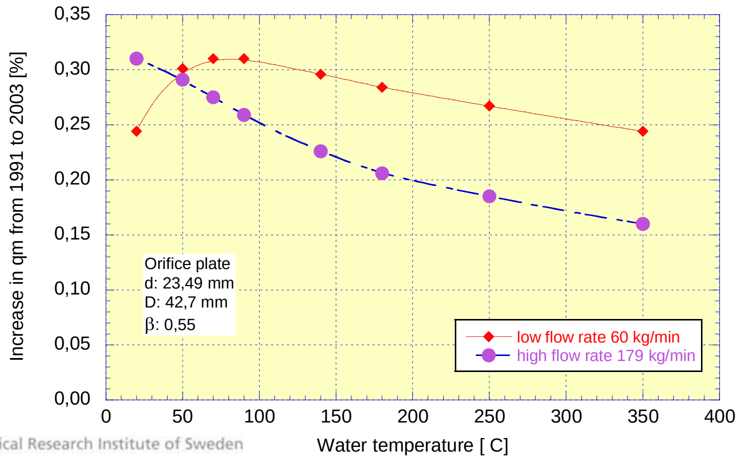
Changes in flow rate calculation according to ISO 5167 between 1991 and 2003

With the same conditions the latest version of ISO 5167 translates the differential pressure **Δp** to 0,2 - 0,3 % higher flow rate **qm**



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Change in discharge coefficient between versions

Steam at ~12 bar and ~188 ºC

Δp [Pa]	qm [kg/s]	C **1991**	C **2003**	Diff [%]
2573	0,540	0,59890	0,60072	0,30%
5030	0,753	0,59835	0,59973	0,23%
9943	1,058	0,59792	0,59885	0,16%
15031	1,300	0,59771	0,59838	0,11%

The change in discharge coefficient decreases with increasing flow rate.

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How are a dp-devices often used?

- The primary flow device is bought with a belonging discharge coefficient C – (one value).
  - calculated to a standard for a specified application (medium, nominal flow rate, pressure, temperature ⇨ Re_D)

    or
  - calibrated in a similar reference condition ⇨ Re_D
- Actual flow q_m(act) is calculated in relation to nominal flow rate q_m(nom) using the square root dependency from Δp

$$q_m(\text{act}) = \sqrt{\frac{\Delta p(\text{act})}{\Delta p(\text{nom})}} \cdot q_m(\text{nom})$$

- For a different application a new relation q_n ⇦⇨ Δp must be applied
- What must be known to calculated flow rate correctly?

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How correct does the simplified model work?

$$q_m(\text{act}) = \sqrt{\frac{\Delta p(\text{act})}{\Delta p(\text{nom})}} \cdot q_m(\text{nom})$$

Example for orifice plate
In water at 90 ºC
Δp = 0,1 bar (10000 Pa)
β = 0,7361
Re= ~540 000

Change in indicated Δp	Change in Calculated flow qn	Error in simplified calculation
+ 1%	0,5 %	0,002 %
+10 %	-4,86 %	0,023 %
-10%	-5,11 %	-0,026 %

Conclusion: The formula works well if **only** Δp changes

Question: What happens if temperature, viscosity or media pressure varies?

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Not registered process parameters changes lead to measurement errors

Example: Hot water flow at 90 ºC

Increase in temperature **ΔT=3 ºC** (influences directly and indirectly)
viscosity -3,17 %, density -0,21 %, Re +3,15 %, C -0,02 %
FLOW RATE Δq_m -0,12 %

Increase in viscosity **$\Delta\mu_1$=3 %** (influences indirectly)
Re -2,89 %, C + 0,02 %,
FLOW RATE Δq_m +0,02 %

Increase in density **Δρ=0,3 %** (influences directly)
Re +1,49 %, C - 0,001 %,
FLOW RATE Δq_m +0,15 %

Errors do not add statistically!

What more information is needed?

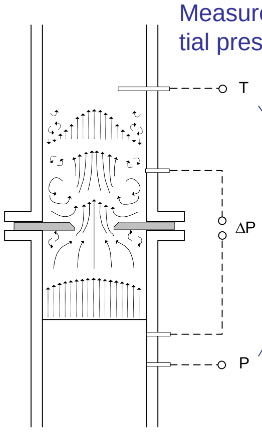
qm calculated from Δp if everything else is known →

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{2\Delta p \cdot \rho_1}$$

Measured with differential pressure transducer

Calculation parameters for mass flow q_m:

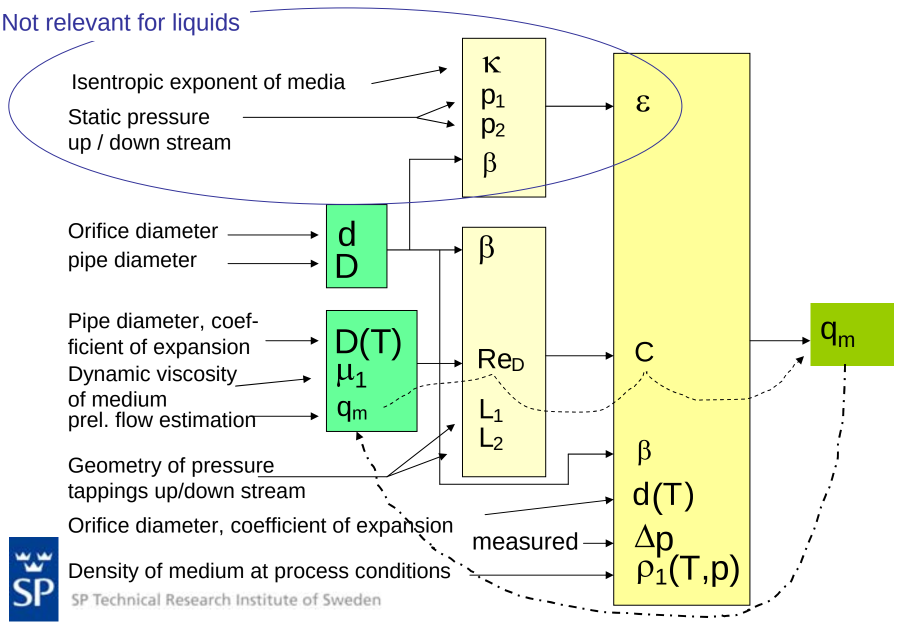
- Pressure difference **Δp**
- Density of medium ρ_1
- Orifice diameter **d**
- Diameter relation **β=d/D**
- Expansibility factor **ε**
- Discharge Coefficient **C**



Measurement computer or intelligent tansmitter

Except β all other factors change with pressure and/or temperature

How are the variables and parameters interrelated?



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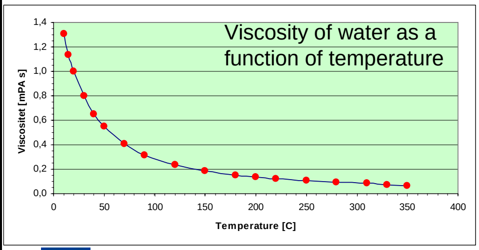
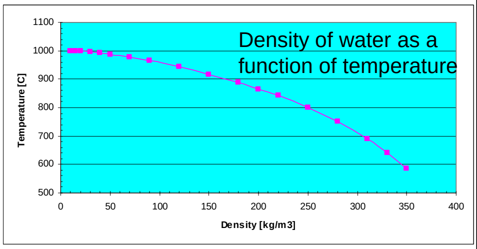
Necessary knowledge about process conditions

How much does viscosity change with temperature?
How much does density change with temperature?
How much does density change with pressure (steam)?
How much does temperature change with pressure (steam)?

Viscosity and density of water
as a function of temperature

Important for calculating
Reynolds number $\mathbf{Re_D}$
Discharge coefficient **C**
(and Expansion coefficient ε)





For hot water these relations are reasonably well known - IAPWS

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Reference calculation for testing - simulating saturated steam

Iterative calculation of flow rate
Assume C2 =0,61
Calculate qm2
Calculate ReD1

Calculate C1
Calculate qm1
Calculate ReD
Calculate C

Calculate qm

Calculated Process parameters

Medium:	Steam	calculation according to EN ISO 5167-2:2003														
	188	°C	Line pressure (saturation)			12	bar									
Set differetial pressure	Calculated Mass flow rate q_m	Calculated expansion coefficient ε	Calculated discharge coefficient C	Calculated Reynolds number Re_D	qm 1	C1	ReD 1	qm 2	C 2	P1	P2/P1	P2	ρ	κ	$\mu 1$	T
[Pa]	[kg/h]		[ ]	[ ]	[kg/s]	[ ]	[ ]	[kg/s]	[ ]	[Pa] abs		[Pa] abs	[kg/m^3]		[kg/m/s] [Pas]	[°C]
2573,395	0,5396	0,9992	**0,60072**	448289	0,540	0,60067	455254	0,548	0,61	1186063	0,9978	1183490	6,0569	1,29774	1,528E-05	187,45
5029,804	0,7533	0,9983	**0,59973**	625684	0,753	0,59968	636448	0,766	0,61	1188520	0,9958	1183490	6,0689	1,29771	1,529E-05	187,55
9942,571	1,0580	0,9967	**0,59885**	878355	1,058	0,59881	894770	1,078	0,61	1193433	0,9917	1183490	6,0930	1,29766	1,529E-05	187,74
15000,058	1,3087	0,9952	**0,59836**	1084211	1,309	0,59832	1105373	1,334	0,61	1217000	0,9877	1183490	6,2083	1,29743	1,532E-05	188,66
	159	°C	Line pressure (saturation)			6	bar									
2573,406	0,3905	0,9983	**0,60157**	346925	0,391	0,60152	351815	0,396	0,61	601205	0,9957	598632	3,1747	1,30499	1,430E-05	158,90
5029,833	0,5452	0,9968	**0,60048**	484352	0,546	0,60043	492074	0,554	0,61	603662	0,9917	598632	3,1870	1,30495	1,430E-05	159,06
9942,588	0,7658	0,9936	**0,59951**	679836	0,767	0,59946	691791	0,780	0,61	608575	0,9837	598632	3,2115	1,30487	1,431E-05	159,38
15030,870	0,9415	0,9905	**0,59898**	835102	0,942	0,59893	850533	0,960	0,61	613663	0,9755	598632	3,2369	1,30479	1,433E-05	159,71

Reference flow

Set upstream pressure

Set downstream pressure

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How is flow measurement affected?

Unrecognized process parameter change:

Temperature change + 1,5 ºC at 90 ºC
+ 3 ºC at 200 ºC

Temperature influences flow rate q_m

directly

indirectly

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} d^2 \sqrt{2\Delta p \cdot \rho_1}$$

$$C = f(Re_D; \beta; L)$$

$$Re = \frac{4 \cdot q_m}{\pi \cdot \mu_1 \cdot D}$$

Change in Density and Viscosity
90 +1,5 ºC ➪ -0,10 % ➪ -1,72 %
200 + 3 ºC ➪ -0,38 % ➪ -1,52 %

Δp = is assumed constant

Flow changes at high low flow
90 +1,5 ºC ➪ -0,05 to -0,06 %
200 + 3 ºC ➪ -0,18 to -0,19 %

Effect on flow rate due to an unrecognized temperature increase.

Orifice/pipe
d: 23,491 mm
D: 42,7 mm
β: 0,5501

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How is flow measurement affected?

Unrecognized process parameter change: **Viscosity change:** + 1 % or + 2 % at 90 and 200 ºC

Viscosity influences flow rate indirectly

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{2\Delta p \cdot \rho_1}$$

$$C = f(Re_D; \beta; L) \qquad Re = \frac{4 \cdot q_m}{\pi \cdot \mu_1 \cdot D}$$

Δp = is assumed constant

Flow changes at 90 ºC high low flow

$\Delta\mu_1$=1% ⇨ 0,003 to 0,005 %

$\Delta\mu 1$=2% ⇨ 0,006 to 0,010 %

Orifice/pipe
d: 23,491 mm
D: 42,7 mm
β: 0,5501

Flow changes at 200 ºC

$\Delta\mu_1$=1% ⇨ 0,004 to 0,007 %

$\Delta\mu_1$=2% ⇨ 0,008 to 0,014 %

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Both flow rate and temperature have marginal influence

How is flow measurement affected?

Unrealized error in pipe diameter **D** +0,5 mm or +1 mm at 90 ºC at 200 ºC

Pipe diameter influences flow rate indirectly

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{2\Delta p \cdot \rho_1}$$

$$C = f(Re_D; \beta; L) \qquad \beta = \frac{d}{D} \qquad Re = \frac{4 \cdot q_m}{\pi \cdot \mu_1 \cdot D}$$

Δp = is assumed constant

ΔD = 0,5 mm ⇨ 1,17 % of D
ΔD = 1 mm ⇨ 2,34 %
ΔD = 0,5 mm ⇨ Δβ -1,16 %
ΔD = 1 mm ⇨ Δβ -2,29 %

Orifice/pipe
d: 23,491 mm
D: 42,7 mm
β: 0,5501

Flow changes at 90 ºC high low flow

ΔD=0,5 mm ⇨ -0,25 to -0,26 %

ΔD = 1 mm ⇨ -0,49 to -0,51 %

Flow changes at 200 ºC

ΔD=0,5 mm ⇨ -0,249 to -0,254 %

ΔD = 1 mm ⇨ -0,483 to -0,496 %

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The flow rate and temperature influences marginal

How is flow measurement affected?

Unrealized error in orifice diameter **d** +0,05 mm or +0,1 mm at 90 ºC
at 200 ºC

Orifice diameter influences flow rate

directly — indirectly

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} d^2 \sqrt{2\Delta p \cdot \rho_1}$$

$$C = f(Re_D; \beta; L) \qquad \beta = \frac{d}{D}$$

Δp = is assumed constant

Δd = 0,05 mm ⇨ 0,21 % of d
Δd = 0,1 mm ⇨ 0,43 % of d
Δd = 0,05 mm ⇨ Δβ -0,21 %
Δd = 0,1 mm ⇨ Δβ -0,43 %

Orifice/pipe
d: 23,491 mm
D: 42,7 mm
β: 0,5501

Flow changes at 90 ºC — high — low flow
+0,05 mm ⇨ -0,473 to -0,474 %
+0,1 mm ⇨ -0,948 to -0,950 %

Flow changes at 200 ºC
+0,5 mm ⇨ -0,472 to -0,473 %
+1 mm ⇨ -0,946 to -0,947 %

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The flow rate and temperature influences marginal

Uncertainty in discharge coefficient C (ISO 5167)

Venturi tubes: U(C) depends on production method	a) casted		0,7 %
	b) machined		1,0 %
	c) welded		1,5 %
Venturi nozzles.	$U(C) = (1{,}2 + 1{,}5 \cdot \beta^4)\%$	β=0,736:	1,64 %
ISA nozzles	$U(C) = 0{,}8\%$ if $\beta \le 0{,}6$		0,8 %
	$U(C) = (2 \cdot \beta - 0{,}4)\%$ if $\beta > 0{,}6$	β=0,736:	1,072 %
Orifice plates	U(C) = (0,7- β) %	for β 0,1 to 0,2	0,6 – 0,5 %
	U(C) = 0,5 %	for β 0,2 to 0,6	0,5 %
	U(C) = (1,667β–0,5) %	for β 0,6 to 0,75	0,5 – 0,75 %
If D<71,12 mm	$U(C) = +0{,}9 \cdot (0{,}75 - \beta) \cdot \left(2{,}8 - \frac{D}{25{,}4}\right)\%$		
		D = 70 mm β = 0,3	+0,018 %
		D = 60 mm β = 0,4	+1,38 %
If moreover β > 0,5 och ReD < 10 000			+0,5 %

Uncertainty in expansibility factor ε

Uncertainty depends on geometry and pressure conditions.
With β = 0,7361 (d=73,61 mm / D=100mm)
ΔP = 15000 Pa (0,15 bar); P1 = 115400 Pa (1,15 bar absolute)
κ = 1,399 (for air at 50 °C)

Venturi tubes	1,64 %
Venturi n	,64 %
ISA nozzle	0,26 %
Orifice plates U(ε) ... % $\kappa \cdot p_1$	0,336 %

Not relevant
when measuring water flow

Problems with direct temperature and density measurement

- Fluid temperature and density should be measured 5 – 15 D downstream from orifice plate in order not disturb flow.
- Reynolds no Re_D needing this information apply however for upstream conditions.
- For very accurate measurements (especially non ideal gases) the temperature drop over the orifice must be calculated:

$$\Delta T = \mu_{JT} \cdot \Delta\varpi$$

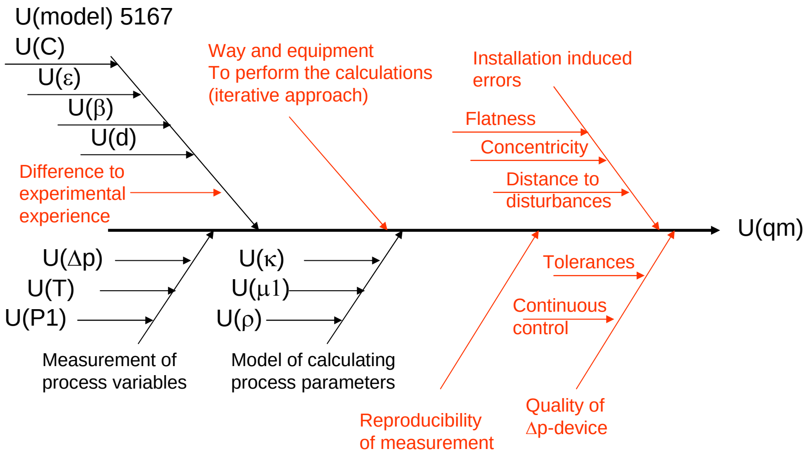
$$\mu_{JT} = \frac{R_u \cdot T^2}{p \cdot c_{m,p}} \cdot \left.\frac{\partial Z}{\partial T}\right|_p \qquad \Delta\varpi = \frac{\sqrt{1-\beta^4 \cdot (1-C^2)} - C\beta^2}{\sqrt{1-\beta^4 \cdot (1-C^2)} + C\beta^2} \cdot \Delta p$$

Joule Thomson coefficient
R_u: universal gas constant
T: absolute Temperature
p: static pressure in medium
$c_{m,p}$: molar heatcapacitet at const. p
Z: compressibility factor

Pressure drop over orifice
β: diameter ratio
C: discharge coefficient
Δp: pressure difference

$$\Delta\varpi \cong 1 - \beta^{1,9} \Delta p$$

What uncertainties then must we expect in measurement?



Analysis of the measurement uncertainty according to GUM for an idealized situation using GUM-Workbench

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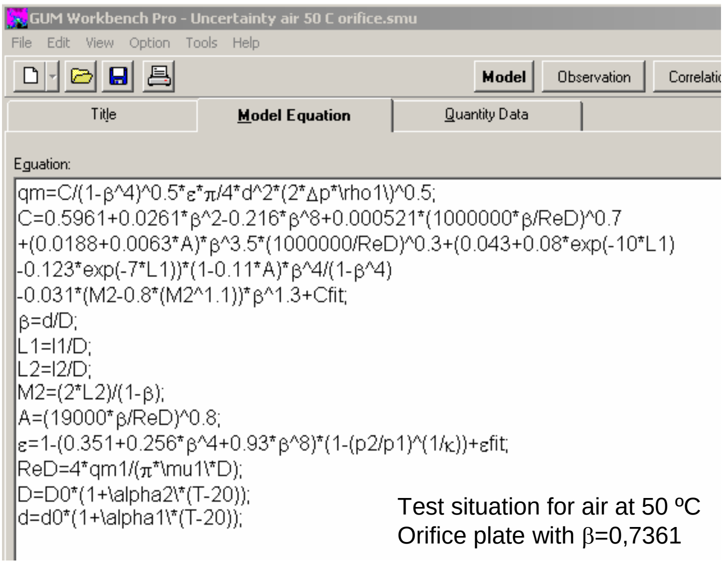
Model equation in GUM Workbench



Test situation for air at 50 ºC
Orifice plate with β=0,7361

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Variable declaration

Quantity	Unit	Definition
ε		Expansion factor
π		constant
d	m	orifice diameter
Δp	Pa	pressure drop
\rho1\	kg/m3	medium density
ReD		Reynolds number
A		Area factor function of beta and Reynolds number
L1	m	Realtion upstream tapping length to to pipediameter
M2	m	relation down stream tapping length to 1-beta
Cfit		An estimator of the uncertainty of the actual discharge coefficient
D	m	Pipe inner diameter as fuction of temperature
l1	m	Distance upstream tapping to orficie face
L2	m	Realtion downstream tapping length to to pipediameter
l2	m	Distance downstream tapping to orficie face
p2	Pa	Down stream pressure = standard atmosphere
p1	Pa	Upstream pressure
κ		Isentropic coefficient
εfit		An estimator for the uncertainty in the model formula for the expansion factor
qm1	kg/s	estimated mass flow rate
\mu1\		dynamic viscosity
D0	m	Pipe inner diameter at 20 C
\alpha2\	/C	Linear expansion coefficient for pipe
T	C	Actual medium temperature
d0	m	Orifice diameter at 20 C
\alpha1\	/C	Linear expansion coefficient for orifice

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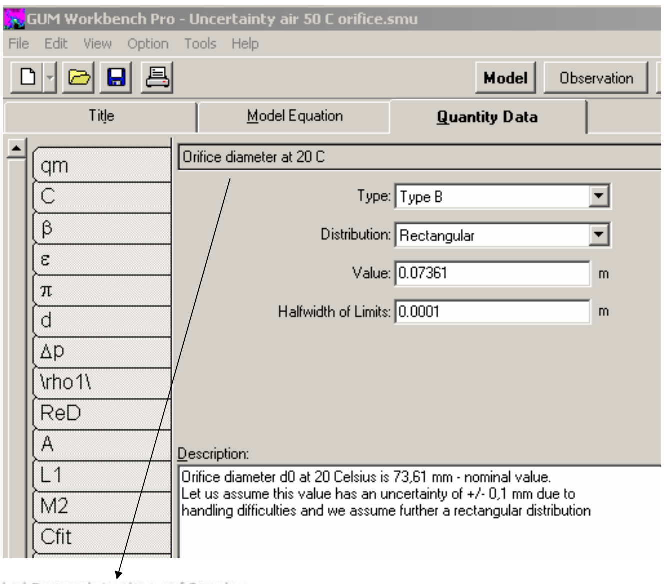
Estimation of all uncertainty components



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The total uncertainty budget

calculated mass flow

Uncertainty Budget:

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
C	0,60507	$2,22\cdot10^{-3}$				
β	0,73610	$2,20\cdot10^{-3}$				
π	3,1415926535898					
d	0,0736475 m	$57,8\cdot10^{-6}$ m				
Δp	2753,40 Pa	6,36 Pa	rectangular	$43\cdot10^{-6}$	$270\cdot10^{-6}$ kg/s	4,2 %
\rho1\	1,10980 kg/m3	$6,35\cdot10^{-3}$ kg/m3	rectangular	0,11	$680\cdot10^{-6}$ kg/s	25,7 %
ReD	$149,79\cdot10^{3}$	2000				
A	0,15002	$1,57\cdot10^{-3}$				
M2	$7,57\cdot10^{-3}$ m	$4,37\cdot10^{-3}$ m				
Cfit	0,0	$2,20\cdot10^{-3}$	normal	0,39	$860\cdot10^{-6}$ kg/s	41,5 %
D	0,100051 m	$289\cdot10^{-6}$ m				
l1	0,0 m	$289\cdot10^{-6}$ m	rectangular	0,098	$28\cdot10^{-6}$ kg/s	0,0 %
L2	$999\cdot10^{-6}$ m	$577\cdot10^{-6}$ m				
l2	$100,0\cdot10^{-6}$ m	$57,7\cdot10^{-6}$ m	rectangular	-0,29	$-17\cdot10^{-6}$ kg/s	0,0 %
p2	$101,300\cdot10^{3}$ Pa	234 Pa	rectangular	$840\cdot10^{-9}$	$200\cdot10^{-6}$ kg/s	1,1 %
p1	$103,873\cdot10^{3}$ Pa	240 Pa	rectangular	$-820\cdot10^{-9}$	$-200\cdot10^{-6}$ kg/s	1,1 %
κ	1,39900	$8,08\cdot10^{-3}$	rectangular	$1,5\cdot10^{-3}$	$12\cdot10^{-6}$ kg/s	0,0 %
εfit	0,0	$328\cdot10^{-6}$	normal	0,24	$79\cdot10^{-6}$ kg/s	0,3 %
qm1	0,23200 kg/s	$1,33\cdot10^{-3}$ kg/s	rectangular	$-8,7\cdot10^{-3}$	$-12\cdot10^{-6}$ kg/s	0,0 %
\mu1\	$19,710\cdot10^{-6}$	$231\cdot10^{-9}$	rectangular	100	$24\cdot10^{-6}$ kg/s	0,0 %
D0	0,100000 m	$289\cdot10^{-6}$ m	rectangular	-1,6	$-460\cdot10^{-6}$ kg/s	12,0 %
\alpha2\	$17,000\cdot10^{-6}$ /C	$981\cdot10^{-9}$ /C	rectangular	-4,8	$-4,7\cdot10^{-6}$ kg/s	0,0 %
T	50,000 C	0,289 C	rectangular	$8,1\cdot10^{-6}$	$2,3\cdot10^{-6}$ kg/s	0,0 %
d0	0,0736100 m	$57,7\cdot10^{-6}$ m	rectangular	8,7	$500\cdot10^{-6}$ kg/s	13,9 %
\alpha1\	$17,000\cdot10^{-6}$ /C	$981\cdot10^{-9}$ /C	rectangular	19	$19\cdot10^{-6}$ kg/s	0,0 %
qm	0,23759 kg/s	$1,34\cdot10^{-3}$ kg/s				

Result:

Value:		Expanded Uncertainty:	Coverage Factor:	Coverage:
0,2376 kg/s	±	1,1 % (relative)	2,00	95% (normal)

Uncertainty contributions at idealized conditions

Process media: **Air at 50 C!**

D=100 mm, d=73,61 mm β=0,7361

ρ=1,1098 kg/m^3, μ1: 1,971*10^{-5} Pa s, κ= 1,399

P1=1,038 bar, Δp=27,53 mbar

Important uncertainty contributions:

- o Discharge coefficient U(C): 0,73 % - at best 0,5 % (41,5 %)
- o Density U(ρ): 1 % (25,7 %)
- o Diameter U(d): 0,1 mm of 73,61 mm (0,14 %) (13,9 %)
- o Diameter U(D): 0,5 mm of 100 mm (0,5 %) (12 %)
- o Differential pressure U(Δp): 0,4 % of reading (4,2 %)
- o Pressure U(P1,P2): 0,4 % of reading (1,1 %)

of calculated flow rate qm=0,2376 ± 0,0027 kg/s (1,1 %)

With iteration process qm=0,2376 kg/s

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Uncertainty contributions at idealized conditions

Process media: **Water at 50 C!**

D=100 mm, d=73,61 mm β=0,7361

ρ=988,1 kg/m^3, μ1: 5,485*10^{-5} Pa s, P1=1,038 bar, Δp=150 mbar

Important uncertainty contributions and their relative importance:	contribution to total uncertainty
➢ Discharge coefficient U(C): 0,73 % - at best 0,5 %	(57,1 %)
➢ Diameter U(d): 0,1 mm of 73,61 mm (0,14 %)	(19,1 %)
➢ Diameter U(D): 0,5 mm of 100 mm (0,5 %)	(16,5 %)
➢ Differential pressure U(Δp): 0,4 % of reading	(5,8 %)
➢ Temperature U(T): 3 ºC	(1,1 %)
➢ Density U(ρ): 1 kg/m^3 (0,1 %)	(0,4 %)
➢ All others contributions below 0,1 %	

Calculated flow rate qm = 16,61 ± 0,159 kg/s (k=2)

± 0,96 %

Installation induced systematic effects add linearly to uncertainty

About measurement quality

Standard ISO 5167 specifies a measurement uncertainty for C och ε if all demands are fulfilled concerning:

- production (according to tolerances)
- installation (with respect to disturbances)
- usage (within the limits of the standard)

The standard expects to examine the orifice plates on a regular basis, to verify pipe measures (roundness, dimension, roughness), to have good knowledge of the process conditions of the medium (i.e. pressure fluctuation, single-phase, pressure > liquid evaporation pressure, temperature > condensation point of gases, $\tau = p_2/p_1 \geq 0{,}75$).

At low gas flow and large temperature differences between medium and surrounding – insulation is necessary.

Any violation of ideal flow conditions must be explored. Swirl and non-symetric flow profiles must be avoided. Flow conditioners are highly recommended.

Total measurement uncertainty

If all process parameters were known without any error:

The best measurement uncertainty (orifice plates) according to standard amounts to:

0.7 % on a 95 % confidence level.

The uncertainty in C, the dominating contribution can possibly be decreased by testing.

But other contributions from installation can easily generate larger uncertainty contributions.

Orifice plates -- their + and -

- Simple and cheap production (especially for big diameters)
- Cheap in installation
- No moving parts - robust
- Works as ”primary element” – no calibration !?
- Good characterized behavior
- Simple function control
- Suits most fluids and gases – even extreme conditions
- Available in many dimensions and a large flow range

- Less dynamic flow range for fixed diameter
- Large pressure loss
- Non linear output, complex calcula-tion - needs urgent calculation help
- Process parameters must be known for flow calculation
- Problems with different phases or flow variations
- Can be sensitive for wear and disposition
- Very sensitive for disturbance and installation caused effects
- To achieve the measurement uncertainties indicated by ISO 5167 many conditions must be fulfilled

Limitations for Orifice Plates – med ISO-5167

Pipe diameter D:	50 – 1200 mm
Reynolds no Re_D:	>3150 turbulent flow is demanded
	No upper limit – but there is no proof
Medium:	single phase liquid, steam or gas
Flow:	steady, no fast changes or pulsations
Pressure tappings:	corner-, flange eller D & D/2 tappings
	no support for other tappings by the standards
Pressure measurement:	Static pressure absolute units
Definition:	p_1 upstream, p_2 downstream
Pressure difference:	$\Delta p = p_1 - p_2$ only for specified tappings
Geometry:	$\beta = d/D$, d orifice diameter, D pipe diameter
	d > 12,5 mm; $0,1 \le \beta \le 0,75$

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To measure flow traceable with Δp devices we need

1. Transfer model between differential pressure Δp measurement and the momentary flow rate qm. ✓
2. Precise definition of the selected primary device with the related discharge coefficient. Use the same standard ISO 5167. ✓
3. Design and production tolerances of all geometric measures that determine the $\Delta p \Leftrightarrow q_m$ relation. ✓
4. Clear advice for installation to keep disturbing effects below a significant error level. ✓
5. Additional contributions to uncertainty due to violation of point 4. - quantified tolerances for distance to certain perturbations. ✓
6. Consider process parameter changes in calculation. ✓
7. **A routine to ensure that original conditions will be preser-ved in future!**
8. **A proven method to determine the discharge coe-fficient C at extreme temperatures and pressure.**

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